Eelgrass Monitoring In Puget Sound: Methods and Preliminary Results of the Submerged Vegetation Monitoring Project

James G. Norris *and* ***Sandy Wyllie-Echeverria***
Marine Resources Consultants

John R. Skalski
Skalski Statistical Services

Richard C. Zimmerman
Consultant

Abstract
Eelgrass *(Zostera marina)* is an important nearshore resource. In order to monitor changes in the abundance and distribution of this habitat type, the Nearshore Habitat component of the Puget Sound Ambient Monitoring Program initiated a Submerged Vegetation Monitoring Project. We are using a rotational random sampling plan with partial replacement. One fifth of the selected sample units are replaced each year, and once chosen, the unit is sampled for five consecutive years. We designated two types of sample units: 1,000 m sections of shoreline (potential 'fringe' eelgrass habitat) and eelgrass 'flats' (eelgrass beds wider than 1000 m). In summer 2000, we sampled 68 stations throughout Puget Sound including the Straits of Juan de Fuca. At each station we used underwater videography on a line transect to estimate eelgrass abundance, patchiness index, and average maximum and minimum depths. At 28 sites, we collected whole plant samples using a van Veen benthic grab to estimate shoot density, LAI, and shoot/root ratio. Data on the physical properties of the water column (temperature, salinity, DO, pH, turbidity, PAR, and backscatter) at each site can be linked to other data on stressors. The results show sound-wide patterns in overall abundance, density, subtidal extent and variability in eelgrass morphology.

Introduction
The primary monitoring effort for Puget Sound waters is the Puget Sound Ambient Monitoring Program (PSAMP). The geographic scope of the PSAMP includes all the inland marine waters of Washington State, from Cape Flattery to the west, Olympia to the south, and the Canadian border to the north. The Nearshore Habitat Program of the Washington Department of Natural Resources (DNR) represents DNR as a component of the PSAMP and has responsibility to monitor temporal trends in submerged aquatic vegetation in Puget Sound. In 2000, DNR initiated the Submerged Vegetation Monitoring Project to assess spatial patterns and temporal trends in nearshore environmental indicators. The specific goal of this project is to monitor the temporal changes in maximum depth and sound wide distribution of eelgrass (*Zostera marina*). The non-indigenous *Z. japonica* is not a target species for this project.

The Submerged Vegetation Monitoring Project has three phases (Sewell and others 2001). Phase 1 will develop a protocol to monitor broad-scale submerged vegetation (eelgrass) trends in distribution and abundance in Puget Sound. Data collected during the summer of 2000 will be used to test and evaluate the protocol. Results will be reported in the spring of 2001, including recommendations for protocol improvements. Phase 2 will expand monitoring to include other submerged vegetation types and monitor across gradients of stressors (e.g., shoreline development). The number of sites will be increased and monitoring will continue to measure long-term historic changes. Phase 3 will develop programs that monitor submerged habitat at higher spatial and temporal resolutions, and gather experimental evidence on cause-effect interactions to build cause-and-effect models. These programs will address functionality, habitat quality and wildlife usage.

In March 2000, the DNR contracted with Marine Resources Consultants to complete Phase I—develop and test a monitoring protocol. The four specific objectives of the protocol are:

1. Capture temporal trends in eelgrass abundance and distribution in Puget Sound.
2. Allow for analysis of trends over subareas that are defined by considering environmental and/or human use factors.
3. Monitor vegetation parameters that are strong indicators of eelgrass extent and quality.
4. consider environmental and anthropogenic gradients (stressors).

This paper summarizes the methods used during the 2000 field survey and presents some preliminary results. This paper is intended to be a progress report to the Puget Sound research community on the Submerged Vegetation Monitoring Project. Further background information about this project is contained in Sewell and others (2001), and a complete description of the methods is contained in the final project plan (Norris and others 2001). Results from the 2000 survey and an evaluation of the draft protocol will be presented in the final report (Norris and others 2001). In spring 2001 an international review team will evaluate both the 2000 project plan and the final report.

Methods

Site Sampling Plan

We divided potential eelgrass habitat in Puget Sound into two types of sites: “flats” and “fringe.” Flats sites are shallow embayments, expansive tide flats, and river deltas (e.g., Skagit Bay, Dosewallips delta); there were 73 flats sites. Fringe sites are 1,000 m sections of shoreline (as measured by the -20 ft Mean Lower Low Water isobath), each with a relatively narrow band of potential eelgrass habitat; there were 2,353 fringe sites. We further sub-divided fringe sites into two strata based on eelgrass abundance noted in earlier surveys (Berry and others 2001): “low eelgrass” (west of Dungeness Spit; 165 sites) and “high eelgrass” (east of Dungeness Spit; 2,188 sites).

For organizational purposes, we assigned each site to one of five regions: north Puget Sound (nps), San Juan/Straits (sjs), Saratoga/Whidbey (swh), Hood Canal (hdc), and central Puget Sound (cps). We selected six “core” sites (four flats and two fringe) for sampling every year. Of the remaining 69 flats sites, we randomly selected 10 sites for sampling in 2000. We randomly selected 45 of the high eelgrass fringe sites and 6 of the low eelgrass fringe sites for sampling in 2000. Figs. 2 and 3 show the region boundaries and the sites sampled during the 2000 survey. In subsequent years, a rotational design with partial replacement will be used (Table 1). This design calls for 20% of the sites sampled in a given year to be replaced the following year and a waiting period of five years before a site can rejoin the sampling pool. Thus, once a site is selected, it will be sampled for five continuous years, after which it must wait another five years before it can be selected again. Over a 50-year monitoring period only 8 of the 69 flats sites are never sampled. Among the 61 sites that are sampled 29, 21, 8, and 3 sites have 1, 2, 3, and 4 five-year sampling periods, respectively.

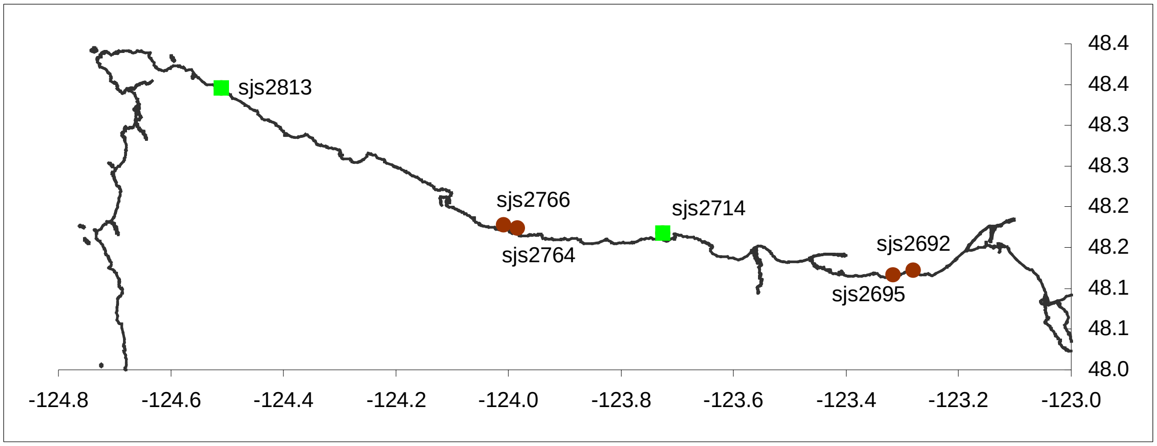

Figure 1. Sites sampled in the "low eelgrass" fringe stratum during the 2000 field survey. Benthic grab sampling was conducted at sites sjs2813 and sjs2714

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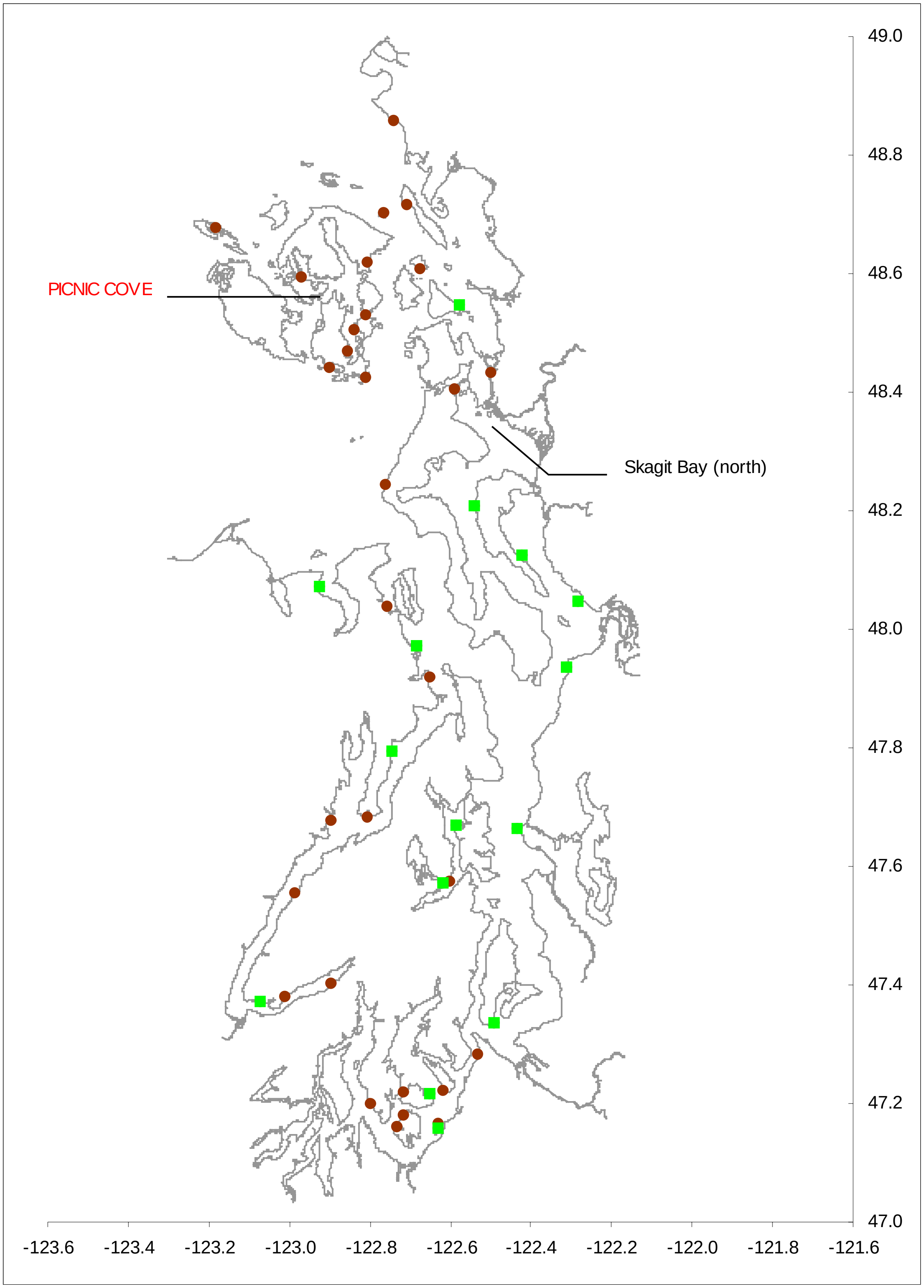


Figure 2. Sites sampled in the "high eelgrass" stratum during the 2000 field survey. "Core" sites are named in red (all caps font). "Flats" sites are named in black (lower case font). "Fringe" sites without grab sampling are shown as brown dots. "Fringe" sites with grab sampling are shown as green squares. Dashed pink lines delineate regions.

Table 1. Flats sites sampling plan from 2000 to 2030.

	Site	00					05					10					15					20					25					30
1	Drayton Harbor (west)							x	x	x	x	x																				
2	Drayton Harbor (east)																	x	x	x	x	x										
3	Birch Bay					x	x	x	x	x																						
4	Lummi Flats (north)																															x
5	Lummi Flats (middle)													x	x	x	x	x														
6	Lummi Flats (south)					x	x	x	x	x																						
7	Portage Bay (north)								x	x	x	x	x												x	x	x	x	x			
8	Portage Bay (south)																										x	x	x	x	x	
9	Nooksack Delta (west)																						x	x	x	x	x					
10	Nooksack Delta (east)																										x	x	x	x	x	
11	Samish Bay (north)																															
12	Samish Bay (south)																															
13	Padilla Bay (north)	x	x	x	x																											
14	Padilla Bay (south)																x	x	x	x	x											
15	Fidalgo Bay (west)																															
16	Fidalgo Bay (east)				x	x	x	x	x							x	x	x	x	x												
17	Bowman Bay																					x	x	x	x	x						
18	Similk Bay	x	x	x	x	x																										
19	Skagit Flat N																							x	x	x	x	x				
20	Skagit Bay (north)	x	x	x	x	x																										
21	Skagit Bay (south)												x	x	x	x	x															
22	Port Susan (west)																															
23	Port Susan (middle)																														x	x
24	Port Susan (east)																															
25	Tulalip Bay																x	x	x	x	x											
26	Snohomish Delta (north)															x	x	x	x	x												
27	Snohomish Delta (middle)		x	x	x	x	x																									
28	Snohomish Delta (south)	x	x	x	x																											
29	Coronet Bay												x	x	x	x	x												x	x	x	x
30	Cultus Bay																															
31	Oak Harbor																															
32	Dugualla Bay						x	x	x	x	x																					
33	Quartermaster Harbor																															
34	Nisqually (west)																					x	x	x	x	x						
35	Nisqually (east)	x	x	x																	x	x	x	x	x							
36	Eagle Harbor																															
37	Wing Point																															
38	Port Madison													x	x	x	x	x							x	x	x	x	x			
39	Liberty Bay																															
40	Miller Bay																	x	x	x	x	x										
41	Dosewallips Delta										x	x	x	x	x																	
42	Quilcene Bay				x	x	x	x	x										x	x	x	x	x									
43	Dabob Bay	x	x	x																												
44	Case Shoal									x	x	x	x	x																		
45	Hood Head																															

Table 1 continues on next page…

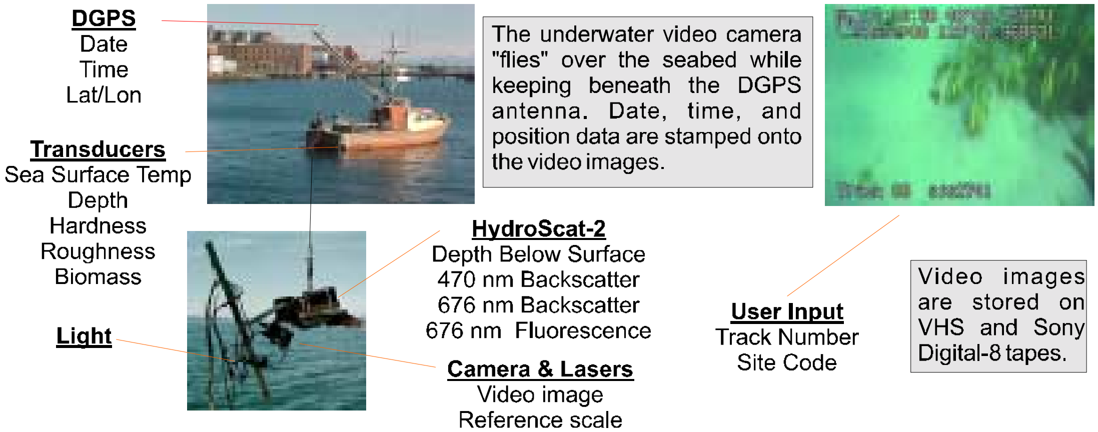
Table 1. Concluded.

46	Kilisut Harbor																															
47	Travis Spit	x	x																													
48	Sequim Bay			x	x	x	x	x																							x
49	Old Town																											x	x	x	x	x
50	Dungeness Bay		x	x	x	x	x																									
51	Prevost Harbor																															
52	Nelson Bay										x	x	x	x	x						x	x	x	x	x						x	x
53	Westcott Bay	x										x	x	x	x	x							x	x	x	x	x					
54	Garrison Bay														x	x	x	x	x													
55	Mitchell Bay																															
56	False Bay														x	x	x	x	x							x	x	x	x	x		
57	Fisherman's Bay											x	x	x	x	x													x	x	x	x
58	Barlow Bay									x	x	x	x	x						x	x	x	x	x								
59	Mud Bay							x	x	x	x	x																				
60	Hunter Bay	x																		x	x	x	x	x						x	x	x
61	Shoal Bay																															
62	Swifts Bay	x	x																							x	x	x	x	x		
63	Blind Bay																															
64	Squaw Bay								x	x	x	x	x						x	x	x	x	x									
65	Thatcher Bay																															
66	Sucia Island North																							x	x	x	x	x				
67	Fossil Bay			x	x	x	x	x																						x	x	x
68	Secret Harbor																															
69	Eagle Cove						x	x	x	x	x																	x	x	x	x	x

Within-Site Transect Sampling

Within-site transect sampling has two objectives: (1) delineate eelgrass beds at a site; and (2) collect data needed to estimate basal area coverage, minimum and maximum eelgrass depth characteristics, and patchiness index. These parameters were selected because they are strong indicators of eelgrass status, have low seasonal variability, and are cost effective to measure (Sewell and others 2001). The draft protocol does not specify the specific methods of estimating these parameters. However, to estimate these parameters the survey equipment must be capable of simultaneously recording eelgrass presence/absence, position, depth, and time of day. Time of day is required to correct depth measurements to the Mean Lower Low Water (MLLW) datum.

For the 2000 survey we employed underwater videography to conduct transect sampling at each site (Figure 3). Basal area coverage will be estimated using methods described by Norris and others (1997). We define the minimum mapping unit to be 1 m^2 and the minimum eelgrass density to be one eelgrass shoot (i.e., we are estimating eelgrass presence/absence regardless of density). The rotational sampling plan will allow a 5-year trend analysis at each site, similar to that described by Norris and Hutley (1998) for a site in Port Townsend Bay.



Date	Time	Lat	Lon	SST	Depth	Hard	Rough	Bmass	bb470	bb676	fl676	Grass
09/26/00	10:19	9.76	42.97	8.30	17.90	113	0	183	0.0185	0.0164	0.0813	1
09/26/00	10:20	9.76	42.97	8.30	17.90	113	0	260	0.0184	0.0162	0.0829	1
09/26/00	10:20	9.76	42.97	8.30	18.10	113	0	260	0.0181	0.0158	0.0771	1
09/26/00	10:20	9.76	42.97	8.30	18.20	113	0	260	0.0181	0.0158	0.0783	0
09/26/00	10:20	9.76	42.97	8.30	18.50	113	0	260	0.0177	0.0153	0.0755	0

For flats sites, transects are conducted in a grid pattern; for fringe sites, transects are conducted perpendicular to the shoreline. At 1 to 2 sec intervals, data from all sources are integrated and stored in a database. During post-processing, depths are corrected to the Mean Lower Low Water vertical datum (using predicted tide heights adjusted for prediction errors) and eelgrass codes (presence/absence) are added to each record.

Figure 3. Illustration of the underwater videographic survey system.

Benthic Grab Sampling
At all core and flats sites and at one third of the fringe sites (selected randomly) we collected whole plant samples from 10 randomly selected stations using a 0.1 m^2 van Veen benthic grab. Other researchers report that this type of grab retrieves a complete sample of plant material (i.e., above and below ground parts) from a 0.1 m^2 area on the bottom (e.g., Ott 1990; Long and others 1994). The grab stations were randomly selected from the collection of eelgrass observations recorded during the underwater video transect sampling. We counted the shoots from each grab sample to estimate shoot densities. We also measured leaf area and wet-weights of leaves and roots from 30 randomly selected plants collected at each site. These data were used to estimate mean leaf area indices and wet-weight shoot:root ratios.

Water Quality Sampling
At each site we selected a water quality sampling station near the deep-water edge of the observed eelgrass bed. We measured water column profiles for temperature, salinity, conductivity, dissolved oxygen, pH, turbidity, and photosynthetically active radiation (PAR). If the depth exceeded 3 m, we took measurements every 1.0 m, otherwise we took measurements every 0.5 m. Light attenuation coefficients (K_d) were estimated from the PAR profiles as the slope of *ln*(PAR) regressed against depth below the surface. During transect sampling we also continuously measured backscatter at two wavelengths (470 nm and 676 nm) using an instrument attached to the underwater video camera towfish.

Biophysical Model
Recent advances in understanding the dynamics of seagrass physiology (Zimmerman and others 1987; Zimmerman and others 1989; Zimmerman and others 1994; Zimmerman and others 1995a; Zimmerman & Alberte 1996; Zimmerman and others 1997) and seagrass canopy optics (Zimmerman and Mobley 1997) have permitted the construction of a physically accurate model of light-driven photosynthesis that can be used to predict carbon balance of submerged aquatic vegetation, such as seagrasses (Zimmerman in prep). The biophysical model incorporates the spectral light environment (a function of water column turbidity),

light absorption and photosynthetic properties of seagrass leaves and canopy architecture (shoot density, leaf size-frequency distribution, shoot:root ratios) to predict physiological carbon balance and light limited seagrass distributions (shoot density, depth range).

We selected the Dumas Bay core site to evaluate the utility of model predictions for the management and monitoring of submerged aquatic vegetation resources in Puget Sound. Measured bathymetry and water column optical properties at Dumas Bay were used to drive the biophysical model of seagrass productivity. Maps of potential seagrass distributions at Dumas Bay were generated from model predictions for comparison with distributions obtained from underwater videographic transect sampling. Sensitivity of predicted eelgrass distributions to uncertainty in water column turbidity and the ratio of shoot:root biomass were tested using a range of values obtained by field surveys.

Preliminary Results

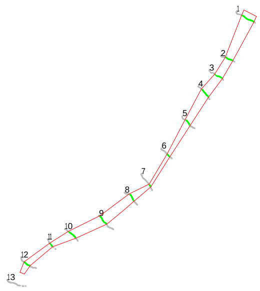
We surveyed approximately 40 nautical miles of shoreline (as measured along the -20 ft MLLW isobath). We conducted 821 underwater video transects and collected water quality profiles at 91 stations (some sites had multiple stations or were sampled on multiple dates). Equipment problems prevented us from collecting PAR data at all Hood Canal sites except Dabob Bay.

We observed significant amounts of eelgrass at all core and flats sites. We did not observe any eelgrass at the following 14 fringe sites (four of which were scheduled grab sites): Cherry Point (nps1342), Guemes Island (nps0669), Trump Island (sjs0695), Charles Island (sjs0736), Green Point west (sjs2695), outer straits (sjs2766), Gertrude Island (cps1245), Treble Point (cps1282), Anderson Island (cps1285), Ketron Island east (cps1296), Tacoma Narrows (cps1804), south Case Inlet (cps1986), Port Washington Canal (cps2154), and East Bremerton (cps2157). The following sites had an abundance of kelp that made it difficult or impossible to adequately survey the entire seabed for eelgrass: Cherry Point (nps1342); Charles Island (sjs0736); Point Partridge (sjs0819); Green Point (sjs2692; sjs2695); and Straits (sjs2764; sjs2766).

We identified *Z. japonica* in grab samples taken at the following sites: Dumas Bay, Similk Bay, Padilla Bay north, and Padilla Bay middle. We also observed surfgrass (*Phyllospadix* spp) at Point Partridge (sjs0819) and east Green Point (sjs2692).

Data analysis for all sites was not completed at the time of this conference. Figure 4 shows an example of a transect sampling data summary (site hdc2433 near Pleasant Harbor in Hood Canal). The small plot shows the track lines, eelgrass observations, and a perimeter line to delineate the eelgrass sample area. The tables summarize data for each track. As the monitoring project continues over the next five years, this site will have five summary sheets similar to the one shown, but with a common perimeter line encompassing all eelgrass observations. The estimated eelgrass fractions for each year (within the common perimeter) will identify trends in abundance.

Eelgrass distributions predicted by the biophysical model were qualitatively consistent with eelgrass distributions found by this study and those reported by previous surveys of Dumas Bay (Norman and others 1995). The model predictions of supportable shoot density (or leaf area index) must be viewed as the upper bounds for light-limited populations, assuming water column conditions used to create the submarine light environment were representative of the annual mean condition at the site. The biophysical model used here did not evaluate other factors that might limit eelgrass density, including nutrient availability, physical disturbances such as dredging operations, burial events or erosive currents. Nor does it include the effects of space competition with macroalgae (e.g., *Ulva* spp., *Enteromorpha* spp., *Gracilaria* spp.) or other seagrasses (e.g., *Zostera japonica*). Thus, disagreement between observed and predicted eelgrass distributions/densities may require investigation into controlling factors other than water column light availability.



Washington State
Department of Natural Resources

Submerged Vegetation Monitoring Project

2000 Field Survey

Site: hdc2433

Track	Date	Track Length	Sample Length	Eelgrass Length	Eelgrass Fraction	Speed (m/s)	Phase Changes
1	8/19/00	62.9	37.7	33.1	0.8773	0.57	0
2	8/19/00	43.2	22.2	20.4	0.9171	0.63	0
3	8/19/00	48.7	22.4	21.6	0.9657	0.61	0
4	8/19/00	47.3	28.4	24.8	0.8755	0.57	0
5	8/19/00	49.7	19.4	16.1	0.8278	0.63	0
6	8/19/00	40.8	10.8	5.8	0.5398	0.64	2
7	8/19/00	54.5	8.4	4.2	0.4996	0.56	0
8	8/19/00	50.2	25.6	18.6	0.7286	0.62	0
9	8/19/00	56.3	29.5	22.3	0.7552	0.53	4
10	8/19/00	48.7	25.8	23.4	0.9089	0.55	0
11	8/19/00	35.9	12.6	8.7	0.6899	0.55	2
12	8/19/00	54.8	19.1	17.1	0.8941	0.53	0
Totals			261.9	216.1			8

Patchiness Index (phase changes per 100 m sample length):	3.06
Average vessel speed (m/s):	0.58
Estimated eelgrass fraction (eelgrass length/sample length):	0.8254
Sample area (area inside eelgrass perimeter):	19,740
Estimated basal area coverage (eelgrass fraction times sample area):	16,293

Track	Min Track Depth	Min Eelgrass Depth	Max Eelgrass Depth	Max Track Depth
1	3.7	-1.5	-12.6	-17.7
2	1.8	-2.4	-10.0	-17.0
3	1.9	-3.6	-15.2	-20.2
4	1.2	-2.8	-13.8	-18.8
5	1.6	-2.8	-9.7	-20.0
6	4.2	-4.3		-12.7
7	3.7		-15.6	-22.8
8	0.7	-3.5	-13.8	-22.7
9	-2.1	-2.2	-15.8	-27.3
10	1.4	-2.8	-16.1	-22.0
11	1.0	-4.1	-10.8	-19.8
12	3.2	-2.6	-11.1	-19.5
Minimum		-4.3	-16.1	
Maximum		-1.5	-9.7	
Mean		-3.0	-13.1	
St Dev		0.8402	2.4213	
cv		0.28	0.18	

Figure 4. Sample transect sampling data summary for site hdc2433.

The biophysical model provided three important findings for the development of a long-term program monitoring submerged aquatic vegetation resources in Puget Sound. First, water column turbidity was identified as a major factor determining eelgrass distributions at Dumas Bay. Model predictions of eelgrass distributions were more sensitive to variations in [TSS] than in [Chl] (Figure 5). This indicates that suspended sediments, either from terrestrial runoff or resuspension of tidal mudflats, and not phytoplankton, probably controls the submarine light environment, and therefore eelgrass distributions at Dumas Bay. This is very similar to the situation in San Francisco Bay were light limitation caused by high water column sediment loads can prevent phytoplankton growth and eelgrass distribution in this otherwise eutrophic estuary (Alpine & Cloern 1988; Zimmerman and others 1991; Zimmerman and others 1995b).

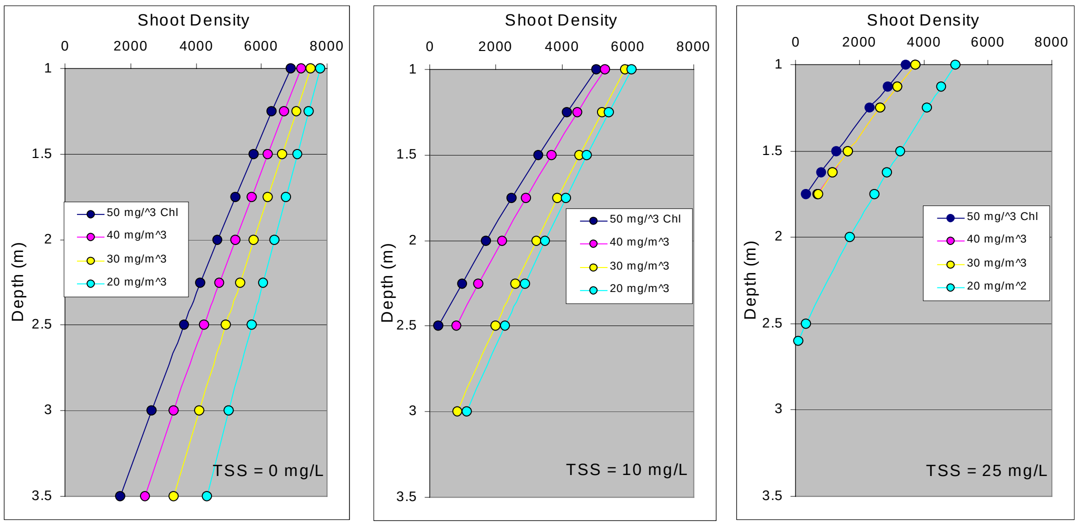


Figure 5. Maximum sustainable density of eelgrass shoots predicted by the biophysical model for different levels of water column [Chl] and [TSS].

Second, this study clearly identified the importance of water column optical properties as modeled by [Chl], and particularly [TSS], to predict eelgrass densities and depth distributions (Figure 6). Consequently, the measurement of these factors, especially with regard to accurate resolution of their spatial and temporal variations, should be given high priority in future efforts to monitor and manage submerged aquatic vegetation resources in Puget Sound.

Third, uncertainty in seagrass morphological parameters, and shoot:root ratios in particular, represent a second-order problem with regard to accurately modeling eelgrass distributions at Dumas Bay. Although field estimates of shoot:root ratio varied by more than a factor of 2, this uncertainty translated into a 5% variation in predicted eelgrass density and depth distribution. Insensitivity of the model to rather large uncertainties in shoot:root ratio makes it difficult to justify extensive field efforts to further refine measurements of plant morphology if the goal is to predict the potential distribution of submerged aquatic vegetation in Puget Sound.

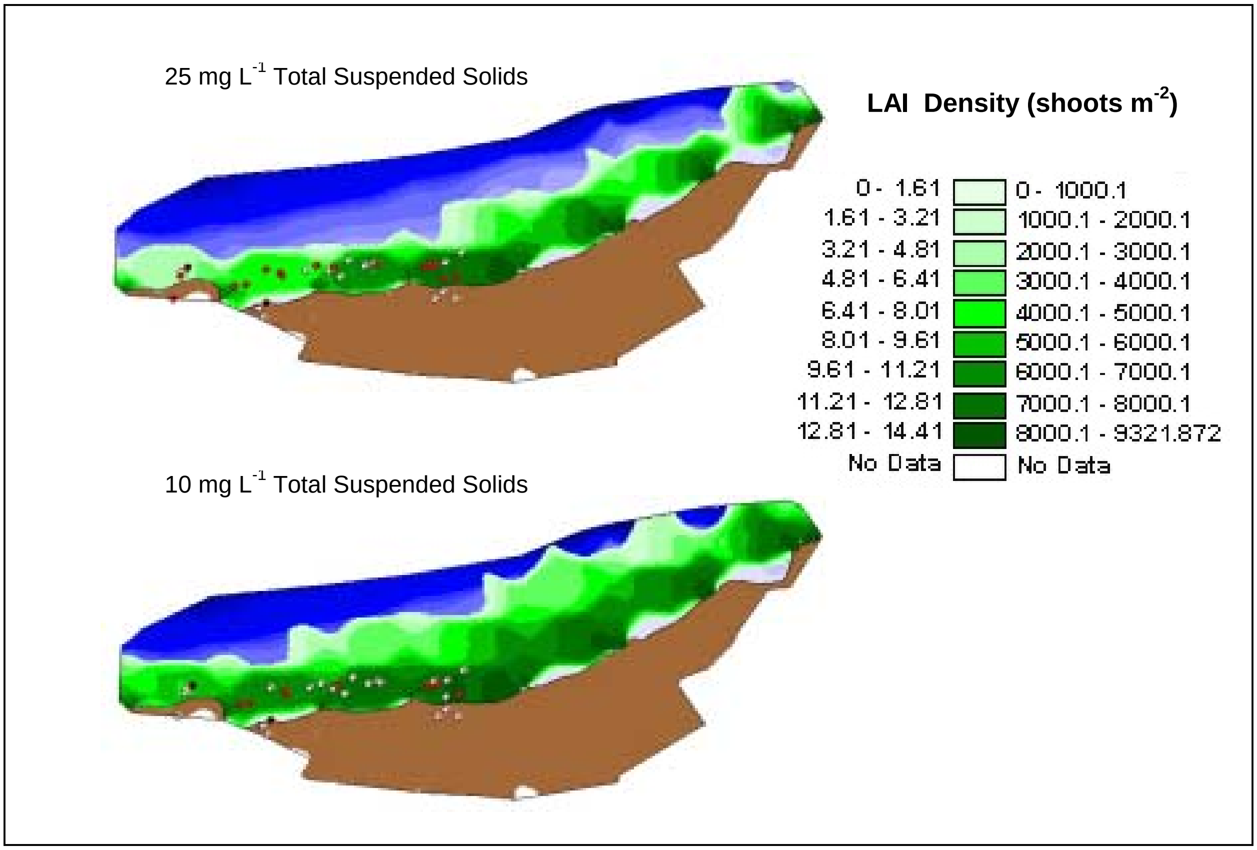


Figure 6. Dumas Bay eelgrass distributions predicted by the biophysical model using two levels of total suspended solids when chlorophyll is constant at 30 mg m^{-3}..

Discussion

This paper is intended to provide the Puget Sound research community with a progress report on the Washington Department of Natural Resources Submerged Vegetation Monitoring Project. The critical parameters estimates of basal area coverage, minimum and maximum eelgrass depth characteristics, and patchiness index for all sites were not available at the time of this conference. Therefore, it is impossible to draw conclusions about the 2000 survey methods at this time. Readers are encouraged to contact the DNR for copies of the Final 2000 Project Plan and the Final 2000 Report.

Acknowledgements

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References

Alcoverro, T, R. Zimmerman, D. Kohrs, and R. Alberte. 1999. Resource allocation and sucrose mobilization in light-limited eelgrass (*Zostera marina* L.). Mar. Ecol. Prog. Ser. **187**: 121-131.

Alpine, A.E., and J.E. Cloern. 1988. Phytoplankton growth rates in a light-limited environment, San Francisco Bay. Mar. Ecol. Prog. Ser. **44**: 167-173.

Bernard, J. E. 1985. A survey to assess the effects of atmospheric deposition on forest vegetation. *In*: Inventory and monitoring for endangered forests, edited by P. Schmid-Hass, International Union of Forest Research Board Organization Conference, Zurich, Switzerland.

Berry, H., J. Harper, M. Dethier, and M. Morris. 2001. Spatial patterns in shoreline habitats: results from the ShoreZone Inventory of Washington State. Puget Sound Research 2001, Puget Sound Water Quality Action Team, P.O. Box 40900, Olympia, WA 98504-0900.

Bickford, C. A., C. E. Mayer, and K. D. Ware. 1963. An efficient design for forest inventory: the Northeastern forest survey. *Journal of Forestry* **61**:826-833.

Cochran, W. G. 1953. Sampling techniques. First edition. Wiley, New York, NY.

Eckler, A. R. 1955. Rotation sampling. *Annals of Mathematical Statistics* 26:664-685.

Hansen, M. H., W. N. Hurwitz, H. Nisselson, and J. Steinberg. 1955. The redesign of the census current population survey. *Journal of the American Statistical Association* **50**:701-719.

Long, B.G. , T.D. Skewes, and J.R. Poiner. 1994. An efficient method for estimating seagrass biomass. Aquatic Botany **47**: 277-291.

Mobley, C. 1989. A numerical model for the computation of radiance distribution in natural waters with wind-roughened surfaces. Limnol. Oceanogr. **34**: 1473-1483.

Norman, D, J. Ruggerone, A. June, and S. Wyllie-Echeverria. 1995. Development of a baseline monitoring program for Dumas Bay, Federal Way, Washington 1995. Department of Community Development, City of Federal Way.

Norris, J.G., and T. Hutley. 1998. Monitoring basal area coverage of eelgrass in Port Townsend Bay, WA. Pages 371-381 *In*: Puget Sound Research ’98 Proceedings, Puget Sound Water Quality Action Team, Olympia, WA.

Norris, J.G., S. Wyllie-Echeverria, T. Mumford, A. Bailey, and T. Turner. 1997. Estimating basal area coverage of subtidal seagrass beds using underwater videography. Aquatic Botany **58**(1997) 269-287.

Norris, J.G., S. Wyllie-Echeverria, J. Skalski, R. Zimmerman, and K. Ewing. 2001. Washington State Department of Natural Resources Submerged Vegetation Monitoring Project Final 2000 Project Plan. Report submitted to the Washington State Department of Natural Resources, Scientific Support Section, 1111 Washington Street SE, 4th Floor, PO Box 47014, Olympia, WA 98502-7014.

Norris, J.G., S. Wyllie-Echeverria, J. Skalski, R. Zimmerman, and K. Ewing. 2001. Washington State Department of Natural Resources Submerged Vegetation Monitoring Project 2000 Final Report. Report submitted to the Washington State Department of Natural Resources, Scientific Support Section, 1111 Washington Street SE, 4th Floor, PO Box 47014, Olympia, WA 98502-7014.

Ott, J. A. 1990. Biomass. Pages 55-60. *In*: R.C. Phillips and C. P. McRoy. Seagrass Research Methods. Paris: Unesco.

Patterson, H. D. 1950. Sampling on successive occasions with partial replacement of units. *Journal of the Royal Statistical Society* **12**:241-255.

Pielou, E.C. 1977. Mathematical Ecology. John Wiley, New York, p 385.

Sen, A. R. 1971. Increased precision in Canadian waterfowl harvest survey through successive sampling. *Journal of Wildlife Management* **35**:664-668.

Sen, A. R. 1979. Sampling theory on repeated occasions with ecological applications. *In*: Sampling biological populations, edited by R. M. Cormack, G. P. Patil, and D. S. Robson, International Co-op House, Fairland, MD, pp. 316-328.

Sewell, A., J. Norris, S. Wyllie-Echeverria, and J. Skalski. 2001. Eelgrass monitoring in Puget Sound: Overview of the Submerged Vegetation Monitoring Project. Puget Sound Research 2001, Puget Sound Water Quality Action Team, P.O. Box 40900, Olympia, WA 98504-0900.

Skalski, J. R. 1990. A design for long-term status and trends monitoring. *Journal of Environmental Management* **30**:139-144.

Smith, R.D. 1989. Anaerobic metabolism in roots of the seagrass *Zostera marina*. 241. Molecular Genetics and Cell Biology. The University of Chicago, Chicago

Smith, R.D., A.M. Pregnall, and R.S. Alberte. 1988. Effects of anaerobiosis on root metabolism of the seagrass *Zostera marina* L. (eelgrass). Mar. Biol. **98**: 131-141.

Sukhatme, P.V. 1954. Sampling theory of surveys with applications. Iowa State College Press, Ames, IO.

Ware, K.D., and T. Cunia. 1962. Continuous forest inventory with partial replacement of samples. *Forest Science Monographs* 3.

Zimmerman, R. (in prep) A bio-optical model of radiative transfer and photosynthesis in seagrass canopies. Limnol. Oceanogr.

Zimmerman, R., and R. Alberte. 1996. Effect of light/dark transition on carbon translocation in eelgrass *Zostera marina* seedlings. Marine Ecology Progress Series **136**: 305-309.

Zimmerman, R., D. Kohrs, and R. Alberte. 1996. Top-down impact through a bottom-up mechanism: the effect of limpet grazing on growth, productivity and carbon allocation of *Zostera marina*. Oecol. **107**: 560-567.

Zimmerman, R., D. Kohrs, D. Steller, and R. Alberte. 1997. Impacts of CO_2 -enrichment on productivity and light requirements of eelgrass. Plant Physiol. **115**: 599-607.

Zimmerman, R., and C. Mobley. 1997. Radiative transfer within seagrass canopies: impact on carbon budgets and light requirements. Ocean Optics XIII Proceedings, SPIE **2963**: 331-336.

Zimmerman, R.C., Cabello-Pasini, and R.S. Alberte. 1994. Modeling daily production of aquatic macrophytes from irradiance measurements: a comparative analysis. Mar. Ecol. Prog. Ser. **114**: 185-196.

Zimmerman, R.C., D.G. Kohrs, D.L.Steller, and R. Alberte. 1995a. Sucrose partitioning in *Zostera marina* L. in relation to photosynthesis and the daily light-dark cycle. Plant Physiol. **108**: 1665-1671.

Zimmerman, R.C., J.L. Reguzzoni, and R.S. Alberte. 1995b. Eelgrass (*Zostera marina* L.) transplants in San Francisco Bay: role of light availability on metabolism, growth and survival. Aquat. Bot. **51**: 67-86.

Zimmerman, R.C., J.L. Reguzzoni, S. Wyllie-Echeverria, M. Josselyn, and R.S. Alberte. 1991. Assessment of environmental suitability for growth of *Zostera marina* L. (eelgrass) in San Francisco Bay. Aquat. Bot. **39**: 353-366.

Zimmerman, R.C., R.D. Smith, and R.S. Alberte. 1987. Is growth of eelgrass nitrogen limited? A numerical simulation of the effects of light and nitrogen on the growth dynamics of *Zostera marina*. Mar. Ecol. Prog. Ser. **41**: 167-176.

Zimmerman, R.C., R.D. Smith, and R.S. Alberte. 1989. Thermal acclimation and whole plant carbon balance in *Zostera marina* L. (eelgrass). J. Exp. Mar. Biol. Ecol. **130**: 93-109.